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Strategy for Monitoring the Exposure and Effects of Contaminants in the Aquatic Environment

L. Désilets and R. Kwiatkowski

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Contents

	Page
ABSTRACT	v
RÉSUMÉ	v
INTRODUCTION	1
1. MAJOR WATER QUALITY ISSUES IN CANADA	2
2. REVIEW OF WQB ACTIVITIES AS RELATED TO WATER QUALITY ISSUES.	3
3. A PROPOSED STRATEGY FOR THE ASSESSMENT OF EXPOSURE AND EFFECTS OF CONTAMINANTS IN THE AQUATIC ENVIRONMENT	5
3.1 A conceptual model of the aquatic environment	6
3.2 The identification of water quality issues	7
3.3 Definition of goals, rationales, and needs	7
3.4 Review of available information	12
3.5 Choice of an operational approach	12
3.6 Sampling design	13
3.7 Station implementation and operation	18
3.8 Data management	18
3.9 Data interpretation	18
3.10 Reporting	21
3.11 Management decisions	21
CONCLUSION	21
ACKNOWLEDGMENTS	22
REFERENCES	22

Tables

		Page
1.	Ambient water quality information needed to assess nine major water quality issues	8
2.	Tools available to assess the quality of aquatic environments	14
3.	Water quality data analysis and interpretation according to various assessment goals	19

Illustrations

Figure 1.	Flowchart describing the steps involved in the proposed strategy for the assessment of exposure and effects of contaminants in the aquatic environment	5
Figure 2.	Model of energy and matter pathways in the aquatic ecosystem	6
Figure 3.	Alterations in the seasonal cycle due to anthropogenic inputs	13
Figure 4.	Temporal cycles involved in the phosphorus cycle	17

Abstract

This paper describes a strategy for monitoring exposure and effects of contaminants in the aquatic environment. Past and present activities of the Water Quality Branch in relation to major water quality issues in Canada are summarized. A framework is then suggested to develop exposure and effect assessments for the issue of contaminants in water. Based on a simple conceptual model of the aquatic environment, this operational framework improves consistency in network design and monitoring programs.

Résumé

Ce document décrit une stratégie de surveillance de la présence et des effets des contaminants dans le milieu aquatique. Les principales préoccupations relatives à la qualité des eaux au Canada sont reliées aux activités historiques et actuelles de la Direction de la qualité des eaux. Un cheminement est ensuite proposé pour faire l'évaluation de la présence et des effets des contaminants en fonction de la préoccupation relative à la qualité de l'eau. Cette méthode opérationnelle est structurée à partir d'un modèle conceptuel simplifié du milieu aquatique, ce qui apporte plus de cohérence dans les réseaux d'échantillonnage et les programmes de surveillance.

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INTRODUCTION

Since the early 1980s, public hearings have shown that contaminants in water are perceived by Canadians as the most important environmental concern (Environment Canada, 1983a). Moreover, the Inquiry on Federal Water Policy (Pearse *et al.*, 1985) devoted a large part of its report to toxic contaminants in water. Recently, the Canadian Environmental Protection Act (CEPA) (Government of Canada, 1988) confirmed the need to follow and control contaminants during their complete life cycle. This is understandable, considering that within Canada 100 000 chemicals are currently in commercial production, 1000 new chemicals are put on the market every year, and 900 chemicals have a production rate greater than one tonne per year. Within the Great Lakes area, more than 600 toxic substances have already been found in the aquatic environment (Environment Canada, 1983b).

Even at very low concentrations, some of these chemicals contaminate the aquatic environment. They can affect the life-supporting characteristics of water, as well as human health. Moreover, these chemicals are often persistent, tend to bioaccumulate through the food chain, and can interact to produce synergistic effects.

Public hearings have shown that interest in contaminants centres on three major questions: What are the problems? Where are the problem areas? What is the danger to human health? People also expect that present uses of water will be maintained and even improved in the future. All these concerns must be taken into account by the Water Quality Branch when planning aquatic environmental quality assessments.

The mandate of the Water Quality Branch (WQB) is "to provide scientific information and advice on the quality of Canada's inland waters to managers, developers, and the public to ensure that this resource is wisely used" (WQB, 1985a). Among the water quality concerns addressed by WQB, the control of contaminants in the environment is identified as a top priority (Environment Canada, 1983c; WQB, 1985a). Information on fate and pathways of various contaminants has also been requested by CEPA (Government of Canada, 1988). The mandate of WQB includes two related tasks: the scientific assessment of the quality of the aquatic environment and the provision of useful and appropriate information to environmental managers and the public. The concerns expressed above require that water quality assessments supply information on the exposure of contaminants (presence, distribution, and

accumulation) as well as on their effects (impairment of aquatic life and water uses, health hazards).

This paper outlines a monitoring strategy for determining the exposure and effects of contaminants in the aquatic environment. It is divided into three sections: (1) present water quality issues in Canada, (2) a review of past and present WQB activities responding to these issues, and (3) a proposed operational framework within which contaminant monitoring of the aquatic environment can be carried out. A basic conceptual model, a flowchart relating assessment activities, and tables describing the tools available for sampling and interpretation are also provided.

The word *contaminants* most often refers to all toxic chemicals that cause a risk to human health or aquatic life. In a broader sense, the word also includes all substances that, once introduced in water, have a deleterious effect on the aquatic environment and impair some water uses. Unless specified, the stricter sense of the word will be used here.

1. MAJOR WATER QUALITY ISSUES IN CANADA

The Task Force on Water Quality Guidelines of the Canadian Council of Resource and Environment Ministers (CCREM, 1985) and the Pearse Inquiry on Federal Water Policy (Pearse *et al.*, 1985) have identified nine major Canadian water quality issues:

1. Pollution of waters used for recreational purposes

2. Contamination of drinking water supplies

3. Impact of land use practices on water quality

4. Impact of toxics and other contaminants on the aquatic environment

5. Impact of water-related development projects on the aquatic ecosystem

6. Impact of LRTAP (long range transport of airborne pollutants) on water quality

7. Chemical contamination of fish

8. Public perceptions of water quality

9. Conflicts over water quality use

This list, which does not indicate any order of priority, shows that water quality issues are a mixed collection of environmental concerns. All, however, are related to chemical contamination of the aquatic environment. Most of these issues concern the impact of contaminants on the environment and directly or indirectly affect people or aquatic life, or both. Many of the issues stem from conflicting uses of water resources.

2. REVIEW OF WQB ACTIVITIES AS RELATED TO WATER QUALITY ISSUES

The topic of contaminants is the latest in a series of priority issues for the Water Quality Branch. During the 1950s, WQB was part of the Department of Energy, Mines and Resources and was known as the Industrial Waters Section, subsequently the Water Quality Division. Sampling at that time assessed the suitability of water for various industrial uses (Thomas, 1953).

In the 1960s, as a contribution to the International Hydrological Decade, a nationwide water quality monitoring program was initiated to assess the background quality (major ions and physical parameters) of Canadian waters. At the end of the 1960s, numerous studies were initiated, especially in the Great Lakes area, to understand and control the rate of eutrophication. At the beginning of the 1970s, WQB became part of the new Department of the Environment. At that time, emerging complex water quality issues, such as mercury and DDT contamination, showed the need for multimedia studies. These studies resulted in regulations on contaminant levels in effluents and the first suggestions for a multimedia monitoring network (WQB, 1977). The mid-1970s saw the emergence of new water quality issues as analytical capabilities for the detection of pollutants in water were improved. Toxics such as heavy metals and organics in drinking water and ground-water contamination from landfills became well-known concerns (Egar, 1978).

By the mid-1970s, Environment Canada was temporarily matched with the Department of Fisheries and, because of the need to assess the quality of the fisheries habitat, multimedia monitoring was again suggested (Fisheries and Environment Canada, 1978). In 1978, a policy statement was made focusing WQB activities on the monitoring of transboundary waters and waterways. In 1980, WQB was asked to add the monitoring of long-term trends in the long range transport of airborne pollutants (LRTAP) in eastern Canada to its activities.

At the beginning of the 1980s, WQB began to develop biomonitoring tools to fill the need for information on bioaccumulation of heavy metals and organics (Shindler, 1981; Clair *et al.*, 1980). A general assessment strategy was developed as a guideline to plan joint assessments as the branch started to negotiate a series of federal-provincial agreements on water quality monitoring (Haffner, 1986). Toxic substances and LRTAP remain the leading concerns for WQB (WQB, 1985a).

In preparing for this paper, Water Quality Branch Activities 1984-1985 (WQB, 1985b) was reviewed to determine how much effort was spent on various types of water quality assessments. The review identified 53 water quality monitoring activities. Most of these activities (70%) were long-term index station networks designed to determine changes in chemical concentrations in water over time. Within these networks, 11% of the activities and 16% of the stations were operated for multimedia sampling.

In the above activities, heavy metals were the most commonly analyzed compounds in water quality assessments (88% of all stations),

followed by nutrients and major ions (80%), physical parameters (57%), pesticides and organics (27%), bacterial counts (11%), and radionuclides (4%).

The above statistics show that ongoing activities of WQB are geared toward long-term measurements of concentrations of major ions, nutrients, or metals in water. These activities are appropriate to assess most water quality issues; however, as pointed out by the General Accounting Office (1981), they provide a limited scope on exposure and effects of hazardous contaminants, especially organics. Difficulties associated with the establishment of exposure and effects monitoring include the following:

- There is no agreed-to holistic approach on the monitoring of contaminants in the aquatic environment.
- There are no Canada-wide standardized techniques for effects biomonitoring within IWD.
- Currently used "effects" measurement techniques were originally designed for wastewater toxicity assessments and are perceived as not sensitive enough to apply to ambient water quality conditions.
- Multimedia organic contaminant sampling is perceived as time consuming and too expensive, often providing conflicting information in the various media.
- Water quality guidelines and objectives are inappropriately perceived to provide environmental protection, thus negating the need for measurements in sediment or biota.

The implementation of a coordinated monitoring plan for exposure and effects of contaminants in the aquatic environment would resolve many of the above difficulties and, therefore, improve the activities of WQB in the following ways:

- by providing a common framework for assessing exposure and effects of contaminants on a regional, as well as national, scale
- by assisting in determining where and in which media aquatic life is affected by contaminants
- by providing the tools necessary to design integrated networks to assess the issues associated with contaminants at the local, regional, or national level
- by assisting in the selection of the appropriate activity for responding to a given water quality issue and determining how this activity relates to other activities, such as water quality objectives or research
- by developing a broader environmental expertise in each region.

3. A PROPOSED STRATEGY FOR THE ASSESSMENT OF EXPOSURE AND EFFECTS OF CONTAMINANTS IN THE AQUATIC ENVIRONMENT

The steps involved in the proposed assessment strategy are summarized in Figure 1 and outlined below.

Most aquatic environmental quality monitoring activities do not define water quality nor do they rely on any basic conceptual model of the aquatic environment, although this model is assumed to exist. In this section, water quality is defined as the state of the aquatic environment, including its biotic and abiotic components, as assessed by measuring the presence and concentrations of contaminants in various media (e.g., water, sediments, and biota), by measuring the effects of these contaminants on aquatic organisms, and by evaluating the resulting suitability of water for various uses.

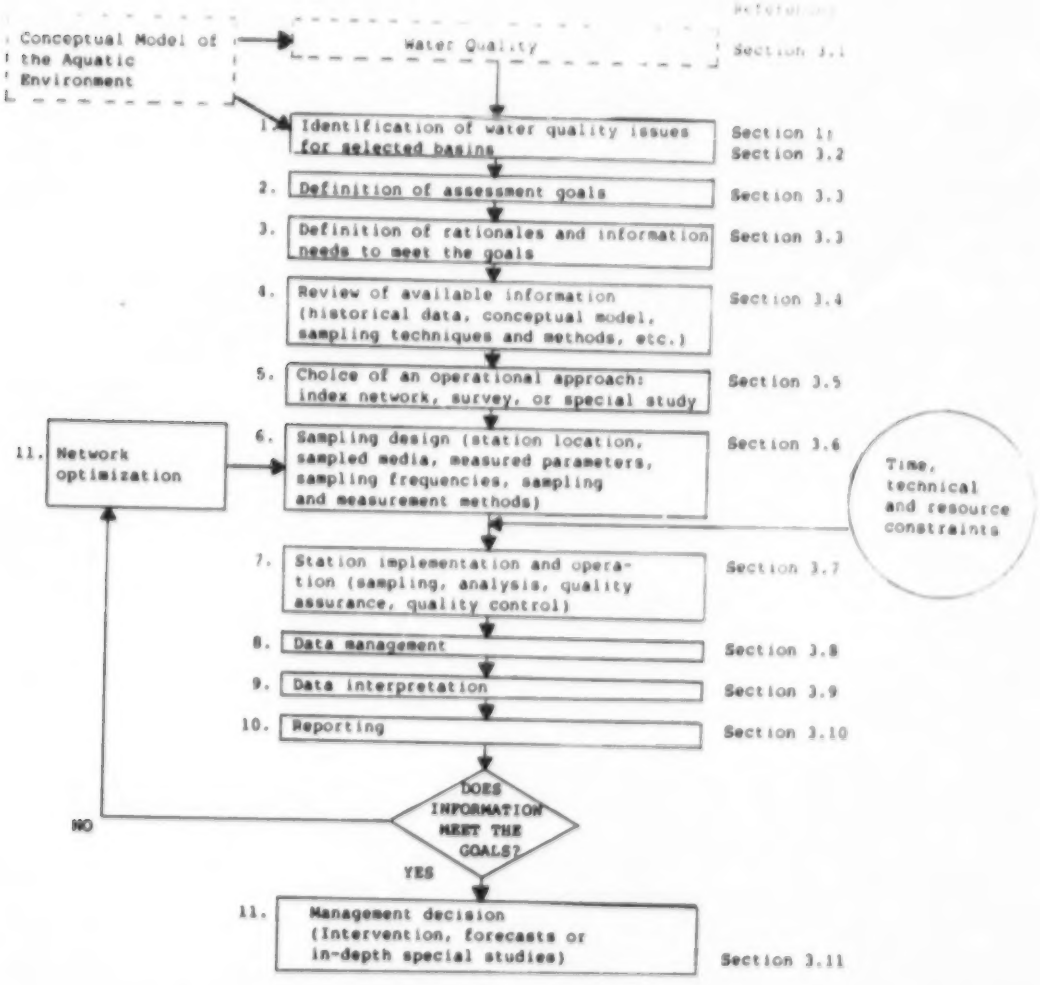
Conceptual Model of the Aquatic Environment
Water Quality
Section 3.1
1. Identification of water quality issues for selected basins
Section 3.2
2. Definition of assessment goals
Section 3.3
3. Definition of rationales and information needs to meet the goals
Section 3.3
4. Review of available information (historical data, conceptual model, sampling techniques and methods, etc.)
Section 3.4
5. Choice of an operational approach: index network, survey, or special study
Section 3.5
6. Sampling design (station location, sampled media, measured parameters, sampling frequencies, sampling and measurement methods)
Section 3.6
11. Network optimization
Time, technical and resource constraints
7. Station implementation and operation (sampling, analysis, quality assurance, quality control)
Section 3.7
8. Data management
Section 3.8
9. Data interpretation
Section 3.9
10. Reporting
Section 3.10
DOES INFORMATION MEET THE GOALS?
NO
YES
11. Management decision (Intervention, forecasts or in-depth special studies)
Section 3.11

Figure 1. Flowchart describing the steps involved in the proposed strategy for the assessment of exposure and effects of contaminants in the aquatic environment (modified from Ward, 1978).

3.1 A Conceptual Model of the Aquatic Environment

It is recommended that a basic conceptual model of the aquatic environment be used for any monitoring activity. A conceptual model provides consistency in network design and a mechanism for formal discussions between involved agencies.

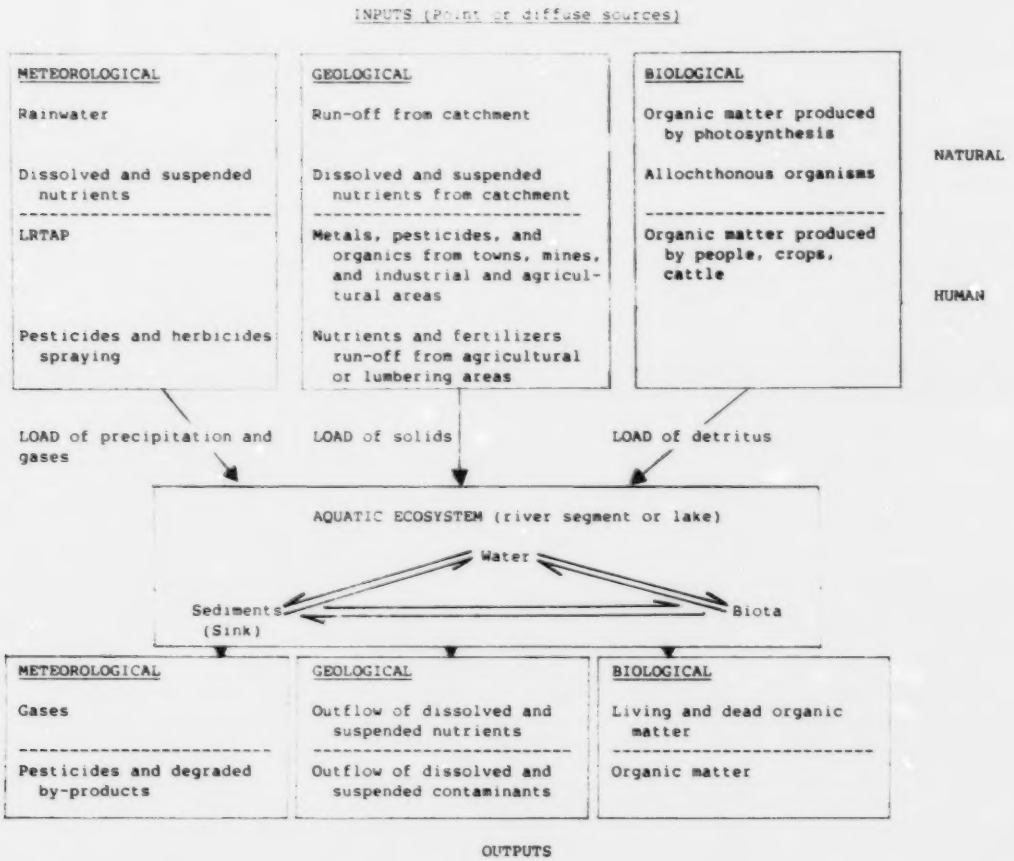

Figure 2. Model of energy and matter (nutrients, minerals, organics) pathways in the aquatic ecosystem (modified from O'Sullivan, 1979).

The movement and fate of contaminants can generally be described and predicted by assuming that the contaminants introduced into the aquatic environment will follow pathways similar to energy and matter. An easy to understand conceptual model of the aquatic ecosystem, whether a river segment or a lake, is illustrated in Figure 2. The model was originally developed by Likens and Bormann (1974) and adapted by O'Sullivan (1979). In this model, inputs are associated with anthropogenic point or diffuse sources, and sediments eventually serve as the major sink. The system is divided into three compartments: water, sediments, and biota. Each compartment acts as a system. For example, water can be divided into dissolved, labile, or

organic forms; sediments can be divided into clay, sand, silt, etc.; and biota can be divided into autotrophs, herbivores, predators, and decomposers. All three compartments are related by food web energy pathways as part of the biogeochemical cycles.

O'Sullivan's (1979) model will be considered in this paper as a starting point for developing a multimedia monitoring framework because of its relative simplicity in showing the sources of contaminants entering the aquatic ecosystem, their pathways, and ultimate fate. The model is easily adapted to the drainage basin perspective by using the hydrological cycle. As most water quality issues stem from conflicting uses of water, the river drainage basin is suggested as the basic unit for contaminant measurement because it provides the necessary framework to study conflicting water uses. The model can also be used to estimate the potential retention time of contaminants in the basin.

O'Sullivan's model is limited in that it needs considerable information for a given contaminant in order to become operational. Although the model will help to understand the movement and fate of contaminants, and thus provide a rationale for a monitoring strategy, it will yield only limited information about how to assess their effects within the biotic compartment. This can be done only through the development of an ecotoxicological model. No satisfactory basic model was found in the literature, although some preliminary work has been done by Hakanson (1984) and Blaise *et al.* (1984). Three types of toxicological effects of contaminants on aquatic organisms have been identified: stress (change in behaviour or physiology), genotoxicity (cancer, reproduction impairment, growth deformities), and acute toxicity. Once exposure and effect indicators are linked in a conceptual model, the assessment design can be made.

3.2 The Identification of Water Quality Issues

As outlined in Figure 1, the identification of water quality issues is the first step in any aquatic environmental quality assessment. An issue is here defined as an environmental problem created by the impairment of a given water use. Section 1 gives major Canadian water quality issues as identified by the Canadian Council of Resource and Environment Ministers (CCREM) and the Pearse Inquiry on Federal Water Policy. Criteria for basin or river segment selection (depending on the area of the studied system) according to various water quality issues can be found in Désilets (1988).

3.3 Definition of Goals, Rationales, and Needs

The definition of goals is identified as step 2 in Figure 1. The goal of any water quality activity basically is what one needs to know to assess an issue. For example, to assess issue 4 of Table 1 (i.e., "Impact of toxics and other contaminants on the aquatic environment"), the following goals could be established: (1) assessment of the degree of exposure of aquatic life to given contaminants and (2) assessment of the resulting state of (or effects on) the environment.

Table 1. Ambient Water Quality Information Needed to Assess Nine Major Water Quality Issues*

	Issue	Goals	Rationales	Information needs
1.	Pollution of waters used for recreational purposes	Assessment of bacterial contamination	Identification and abundance of bacterial indicator species; comparison with guidelines	Exposure
		Assessment of eutrophication status (algal blooms)	Measurement of nutrient concentrations in water; identification and abundance of indicator phytoplankton and macrophyte species; measurement of productivity (biomass, chlo. *a*); algal growth potential bioassays	Both
		Assessment of aesthetic status	Measurement of physical water quality parameters; inventory of algae blooms events	Effects
		Assessment of contact deleterious effects (toxics)	Scannings of organics in water; comparison with guidelines; epidemiological studies	Both
2.	Contamination of drinking water supplies	Assessment of pipe clogging and sediment load	Measurement of physical parameters, suspended sediment load, and organic matter in water	Exposure
		Assessment of eutrophication	Measurement of nutrients and chlo. *a* in water; comparison with guidelines; algal growth potential bioassays; identification and abundance of indicator algae	Both
		Assessment of bacterial contamination	Identification and abundance of bacterial indicator species; comparison with guidelines	Exposure
		Assessment of contamination by toxics	Measurement of metals and organics in vater sediments, and local freshwater species (e.g., minnows); comparison with guidelines; growth inhibition bioassays	Both

* As identified by the Task Force of the CCREM.

Note: In this table, the word contaminants is used in its broad sense.

Table 1. Continued.

	Issue	Goals	Rationales	Information needs
3.	Impact of land use practices on water quality	Depending on land uses: Assessment of soil erosion (agriculture, forestry)	Measurement of sediment load, physical parameters, and major ions in water	Exposure
		Assessment of nutrients runoff (agriculture, urban sewage)	Measurement of nutrients and organic matter concentrations in water and suspended sediments	Exposure
		Assessment of toxics runoff (industries, agriculture, urban sewage, mines, forestry)	Measurement of toxics in water, sediments, and biota	Exposure
		Assessment of effects of runoff (any type)	Measurement of abundance and productivity of indicator aquatic species; stress indicator or physiologic disorder bioassays; saprobic index	Effects
4.	Impact of toxics and other contaminants on the aquatic environment	Assessment of the exposure of aquatic life	Measurement of concentrations of metals and organics (including scannings) in water, sediments, and biota; bioaccumulation bioassays (in lab or field); comparison with guidelines	Exposure
		Assessment of the state of aquatic communities	Lethality, sublethality (metabolic, growth or reproduction inhibition), or genotoxicity bioassays - presence, abundance, and productivity of sedentary indicator indigenous communities (downstream versus upstream ones)	Effects
5.	Impact of water-related development projects on the aquatic ecosystem	Assessment of historical changes in water quality (and limiting factors)	Review of historical data sets to measure a change in physical parameters, nutrients, major ions, or metals in water; measure of sediment loading	Exposure
		Assessment of spatial changes in water quality (and limiting factors)	Measurement of above water quality parameters and sediment load upstream and downstream from the implementation site	Exposure

Table 1. Continued.

Issue	Goals	Rationales	Information needs
	Assessment of historical changes in the state of aquatic life	Review of historical data sets to measure a change in structure or function of aquatic communities	Effect
	Assessment of spatial changes in the state of aquatic life	Measurement and comparison of upstream and downstream structure or function data on indigenous indicator aquatic communities, or using bioassays	Effects
6. Impact of LRTAP on water quality	Assessment of the historical atmospheric inputs and loadings	Measurement of concentration of major ions, metals, and organics in precipitation, water, sediments, and biota; comparison with historical data sets	Exposure
	Assessment of distribution of atmospheric inputs and loadings	Measurement of concentration of major ions, metals and organics in precipitation, water, sediments, and biota	Exposure
	Assessment of historical effects of acidic precipitation	Review and comparison of historical data sets on structure and function of selected communities, or long-term sublethal bioassays	Effects
	Assessment of distribution of effects of acidic precipitation	Measurement of structure and function indices of indicator species of affected communities	Effects
7. Chemical contamination of fish	Assessment of fish exposure	Measurement of metals and organics (including scannings) in fish flesh, selected organs, and total fish (predator, detrivorous, and forage fish); comparison with guidelines; use of bioaccumulation bioassays	Exposure
	Assessment of physiological disorders in fish	Measurement of deformities, stress, growth inhibition, and reproduction impairment using captured specimens or bioassays	Effects
	Assessment of the status of fish communities	Measurement of structure and function of indicator fish communities	Effects

Table 1. Continued.

Issue	Goals	Rationales	Information needs
8. Public perception of water quality	N/A		
9. Conflicts over water quality use	N/A		

The definition of rationales and needs is identified as step 3 of Figure 1. The rationale of a water quality assessment is a statement of what will be measured and how it will be measured to meet the goals. The needs for monitoring activities are the aspect on which these will focus: exposure monitoring versus effects monitoring. In the above example, the exposure of aquatic organisms could be assessed by measuring the concentrations of a given contaminant in various media to establish pathways, fate, and bioavailability. The health of the aquatic organisms (or effects of contaminants) can be assessed by measuring the structure and functions of the various organisms within the aquatic ecosystem, as shown later in Table 2. If preliminary studies have been made, it becomes possible to quantify the importance, the length (e.g., a 10% change in 10 years of data), and the precision of the expected changes to be measured, based on the statistical tests further used to interpret the data (see section 3.9). A complete assessment of the aquatic environment is a complex and expensive task. Structural and functional indicators used as surrogates (see section 3.6) greatly reduce this expense.

Table 1 links the goals, rationales, and assessment needs for each of the Canadian water quality issues identified by CCREM and the Pearse Inquiry.

3.4 Review of Available Information

Review of available information is step 4 of Figure 1. This activity preverts repetition of previous studies, provides information on the proper parameters to be measured and appropriate sampling techniques, and assists in the interpretation of the measurements made and in the development of cause-effect relationships between the quality of the aquatic environment and natural or anthropogenic factors (i.e., geology, hydrology, vegetation, industries, municipalities, land uses, etc.). A review of criteria to assess the importance of various factors that can induce changes in water quality is made by Désilets (1988).

3.5 Choice of an Operational Approach

There are basically three operational approaches that can be used to implement an aquatic environmental quality assessment, depending on the information needs and supporting rationales: index station network, survey, and special study. An index network consists of fixed stations routinely monitored over many years to assess time trends or compliance with water quality objectives. Surveys are short-term activities (usually less than two years) conducted to assess a given issue with respect to spatial trends, establish cause and effect relationships, or develop water quality objectives. Surveys can be made on a recurrent basis. Special studies are short-term activities (usually less than one year), are often intensive, and have very narrowly focused objectives, such as to assess variability in non-studied systems (e.g., preliminary surveys), assess how representative the sampling station sites are (e.g., studies of transects), or evaluate the performance of a new sampling technique. All three approaches are described by Haffner (1986) and Désilets (1988).

The choice of a given sampling approach or a combination of the three outlined above is made at step 5 of Figure 1. This choice is influenced by assessment rationales and available information. Each operational approach outlined corresponds to a statistical field of water quality monitoring: index networks address temporal trends; surveys address spatial trends; and special studies address sample representativeness. Once a selection is made, the basics are set up for sampling design.

3.6 Sampling Design

Sampling design is identified as step 6 of Figure 1. Design starts with station macrolocation and station microlocation (Désilets, 1988). As contaminant analyses are expensive, some authors have suggested various approaches to determine the most appropriate medium or media to sample for the measurement of specific components. Chapman *et al.* (1982), for example, selected the appropriate media (water, sediments, biota) to measure each of EPA's 126 priority pollutants based on their physical (volatility) and chemical (persistence) characteristics. The medium suggested for monitoring 44 of the pollutants was water, however, sediments and biota were the preferred media for 86 and 64 pollutants, respectively.

Sampling media, sampling methods, and parameters to be measured are classified in Table 2. The purpose of this table is not to make a detailed review of sampling and measurement methods for exposure and effects assessments, but rather to provide guidance on their selection and use. Numerous manuals on sampling and measurement techniques have already been published. The following are suggested: Hellawell (1978), Lind (1979), Dodge *et al.* (1981), Environmental Protection Agency (1982), Water Quality Branch (1983), APHA *et al.* (1985), and Environment Canada (1981).

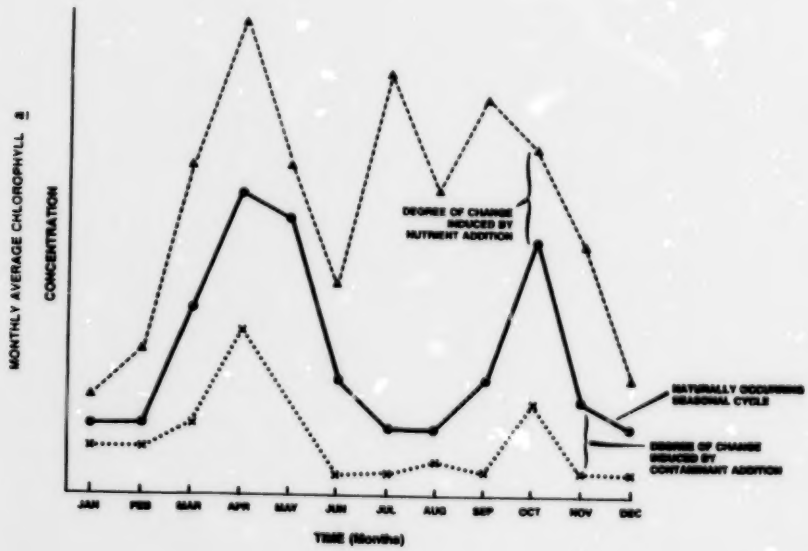

Figure 3. Alterations in the Seasonal Cycle due to Anthropogenic Inputs.

Table 2. Tools Available to Assess the Quality of Aquatic Environments

Sampled media	Compartment	Type of samples	Measurements		
				Effects	
			Exposure indicators	Structure indicators	Function indicators
Water	Water	Grab, or time or depth composite sample (e.g., bottles, pumps)	Analysis of standard parameter sets (major ions, nutrients, metals, organics) or scannings (organics) or radionuclides	N/A	N/A
Water	Bacteria	Surface grab sample	Measurement of limiting factors (light, temperature, O_2, nutrients, toxics, pH)	Bacterial counts of indicator species (e.g., coliforms)	Lethality, metabolic or growth inhibition (e.g., luminescence) genotoxicity or biodegradability bioassays
Water	Phytoplankton	Grab, or surface or depth composite sample (e.g., bottles, pumps)	Measurement of limiting factors (light, temperature, O_2, nutrients, toxics); bioaccumulation bioassays or field data	Identification of species for presence/absence or dominance, diversity	Productivity and growth rate bioassays (e.g., Selenastrum capricornutum)
Sediments	Suspended sediments	Grab, or time or depth composite sample (e.g., traps, pumps, centrifuge)	Analysis of standard parameters sets (particle size, organic content, nutrients, metals, organics) or scannings (organics) or radionuclides	N/A	N/A
Sediments	Bacteria	Surface sample	Measurement of limiting factors (light, O_2, nutrients, toxics)	Identification of indicator species, population density	Growth rate bioassays, mutagenicity bioassay (e.g., Microtox)

Table 2. Continued.

Sampled media	Compartment	Type of samples	Measurements		
			Exposure indicators	Effects: Structure indicators	Effects: Function indicators
Biota	Benthic-organisms (including periphyton)	Grab sample or artificial substrate (colonization); transects	Measurement of limiting factors; analysis of standard sets of metals and organics in indigenous species or caged specimens (e.g., clams)	Identification of species for presence/absence or dominance, diversity	Lethality and growth rate bioassays (e.g., rotifers); biomass/m^2; population density; deformity frequency (e.g., chironomids)
Biota	Predator fish (e.g., pike) or bottom fish (e.g., sucker)	Fishing for all or selected sizes (e.g., nets, electrofishing)	Analysis of fillets (human consumption) or whole body (bio-indicator) or selected organs (bioaccumulation) for standard sets of metals or organics or radionuclides; considering travelling of most individuals	Identification of species for presence/absence or dominance, diversity; measurement of weight, length or age class for selected species; interspecies relationship	Fishing success; population estimate by capture/recapture; physiological condition factor, deformities, diseases (e.g., tumors) stomach content (identification, weight); physiological or behaviour disturbance; sublethal and lethal bioassays; reproduction success
Biota	Forage fish (e.g., minnows)	Fishing for selected species; composite whole fish sample (e.g., traps, seines, electrofishing)	Analysis of standard sets of metals or organics, or scannings of organics, measurement of limiting factors	Identification of species for presence/absence, or dominance, diversity; measurement of weight or length classes; habitat characterization from water quality, interspecies relationship	Absolute or relative abundance, biomass, physiological condition factor; deformities, reproduction success; physiological or behaviour disturbance; lethal and sublethal bioassays

Table 2. Continued.

Sampled media	Compartment	Type of samples	Measurements		
			Exposure indicators	Effects	
				Structure indicators	Function indicators
Sediments	Bottom	Surface or bulk sample, single or composite; (e.g., dredge)	Analysis of particle size, organic content, redox potential, standard parameter sets (nutrients, metals, organics) or scannings (organics) or radionuclides from sediments or elutriates	N/A	N/A
Biota	Macrophytes	Part, whole, or composite sample	Measurement of limiting factors; analysis of standard sets of metals or organics of indicator species for bioaccumulation in indigenous or caged specimen (e.g., weeds, mosses)	Identification of species for presence/absence or dominance, diversity	Biomass (standing crop); algal growth potential bioassay
Biota	Zooplankton	Grab, or surface or depth composite sample (e.g., conical net, pump)	Analysis of standard sets of metals or organics for bioaccumulation; measurement of limiting factors: light, depth, temperature, O_2, pH, toxics, chlo. *a*	Identification of species for presence/absence or dominance, diversity	Lethality or growth rate bioassays (e.g., *Daphnia pulex*); biomass/m^3; population density

A review of the field sampling methods described in the publications suggested above provides numerous examples of intensive surveys or special studies carried out on a small area or stream. This is due to the fact that too many uncontrollable factors (physical conditions, natural cycles, variety of land and water uses, etc.) make detection of anthropogenic impacts difficult (Fig. 3). Long-term trends are difficult to determine for the same reasons. Standardization of various laboratory or field bioassay techniques provides an interesting alternative in that it reduces some of the variability-inducing factors already mentioned. Many bioassay techniques originally developed for effluent monitoring have now been successfully adopted for ambient water quality monitoring purposes. A review of core bioassay methods that can be used by DOE was recently made by the Lab Managers Committee (Sergy, 1987).

The last item to be defined in network design is sampling frequencies. Sampling frequency is influenced by sampling objectives (e.g., establish a 10-year trend), expected precision of the assessment (e.g., 10% confidence interval), and the variability of the system studied. The variability of the aquatic ecosystem is influenced by three factors. An objective of the water quality sampling procedure is to isolate one of those three types of induced variability. These are spatial variability (e.g., the influence of bottom composition on the distribution of benthic organisms), temporal variability (e.g., the various temporal cycles of phosphorus induced by chemical, physical, or biological activities, as illustrated in Figure 4), and natural versus anthropogenic induced variability, as illustrated in Figure 3.

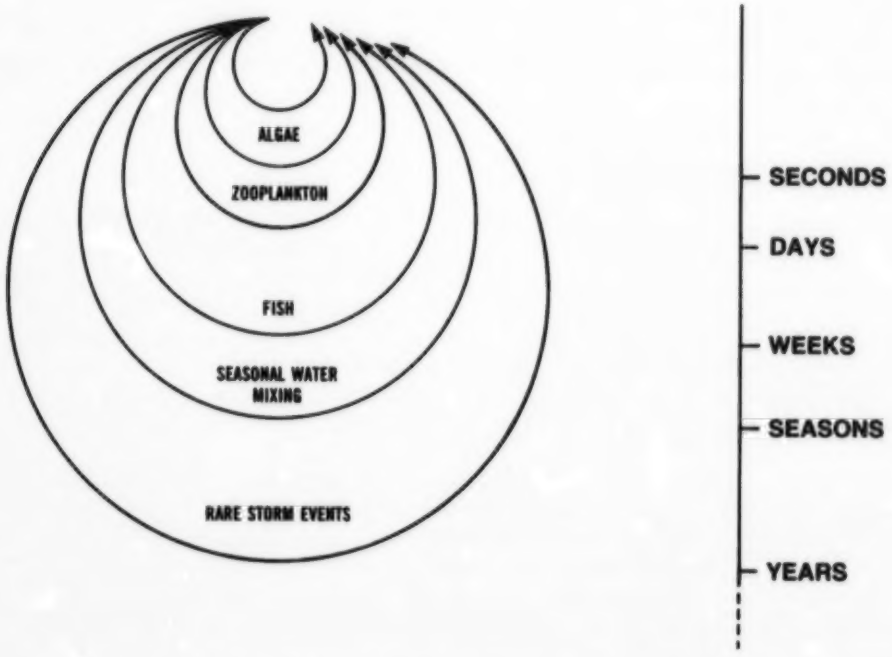

Figure 4. Temporal cycles involved in the phosphorus cycle.

Sampling frequencies can be determined from historical data sets (see section 3.4) or from a preliminary (pilot) study (see section 3.5). It should be pointed out, however, that in most water quality studies, these two activities are absent or underestimated in the planning phase. This often results in sparse and highly variable data and information that does not meet the goals of the assessment (Fig. 1).

3.7 Station Implementation and Operation

Step 7 of Figure 1 is station implementation. The most important aspect of this activity is quality assurance and quality control (QA/QC). QA/QC procedures must be part of all field, laboratory, and data storage operations to ensure data reliability and consistency. Manuals on field quality assurance (Gaskin and Watt, 1987) and on laboratory quality assurance (Agemian, 1987) have been prepared by WQB.

3.8 Data Management

Step 8 is data management. This activity involves two major operations: data interpretation and data archiving. Data interpretation requires that stored data be easy to retrieve in a format useful for statistical analysis. Data archiving requires that the data set be properly described in terms of the project to which it belongs, the responsible officer or agency for the project, and the goals and final publications resulting from the project. Proper archiving will make data available for time series analysis or baseline information by other scientists in the future. Data archiving and retrieval using NAQUADAT are described in Whitlow and Lamb (1983) and WQB (1983). As NAQUADAT was not originally designed to store biological data, a biological data base has been developed by regional staff (Howell *et al.*, 1985).

3.9 Data Interpretation

Step 9, data interpretation, is crucial in any water quality assessment. It must provide the necessary information to answer the hypotheses or questions outlined in the goals at step 2. The quality of interpretation is linked to sampling frequency, number of samples, and sampling design in general, e.g., data variability. The approach used for data interpretation will differ from an "exposure" to an "effects" type assessment. A list of tools available for data analysis and interpretation as related to assessment goals is given in Table 3.

Some basic statistical techniques for analyzing data on concentrations of chemicals in water are described in Sanders *et al.* (1983). A review of available statistical packages for the analysis of chemical or biological data was made by Gertz *et al.* (1984). Recently, two specialized packages on time series analysis were developed for the Inland Waters Directorate (Cluis *et al.*, 1988; McLeod and Hipel, 1987, McLeod *et al.*, 1983).

A review of known statistical methods for studying biotic responses to persistent toxic substances and the importance of these responses to network design was made by Esterby (1986) and Dickson and Cairns (1978). Data interpretation per se follows statistical analysis as outlined above. "Exposure" assessments rely mostly on spatial or temporal trends, which can be illustrated using graphs or maps. "Effects" assessments are more difficult to illustrate when associated with various water uses or health risks. Water quality objectives and guidelines (CCREM, 1987) greatly facilitate data interpretation by providing the necessary environmental yardsticks in terms of maximum tolerance levels for many components in water. Water quality guidelines do not, however, replace "effects" type field data, as they were originally designed as national environmental benchmarks and do not necessarily fit within a local context. Moreover, it must be understood that water quality guidelines should be used in a precursory fashion and need to be supported by effects assessments in order to establish site-specific objectives.

Table 3. Water Quality Data Analysis and Interpretation According to Various Assessment Goals

Common assessment goal	Required information	Appropriate data analytical procedures
a) Background information or baseline conditions of the studied system	Presence and levels of various contaminants in various media	Calculation of medians, minimums, and maximums; interpretation of chemical scannings
	Levels of major ions and nutrients	Median, minimum, and maximum
	Seasonal or annual concentration patterns	Graph of data vs. months; ANOVA between seasons; correlation with hydrological or climatic variables
	Sampling site representativeness	Local spatial (vertical, lateral) variability for each sampling site
b) Spatial distribution or spatial trends of contaminants	Mapping of contaminant concentrations	Station location, class distribution
	Homogeneous zones	Cluster analysis
	Spatial gradients	ANOVA between stations; contrasts; correlation of concentrations with downstream distance (rivers) or orientation (lakes) from point or diffuse sources
c) Determination of long-term trends	Identification of trends in long-term historical data sets	Non-parametric tests such as Mann-Whitney, Lettenmaier, Kendall, depending on the data set; regression within time; analysis of residuals, autocorrelation
d) Identification of real or potential water quality problems	Survey of potential problems	Evaluation of the importance of point or diffuse sources of contaminants (flow, loads)

Table 3. Continued.

Common assessment goal	Required information	Appropriate data analytical procedures
	Assessment of environmental risks	Comparison of measured levels to water quality objectives, guidelines, or regulations; non-compliance frequency and importance
	Assessment of effects of contaminants on aquatic life	Presence/absence of selected species, state of structure (diversity, dominance, etc.) and functions (productivity, etc.) of studied systems; comparison with pristine sites and ecotoxicological data
e) Design of water quality guidelines and objectives	Survey of water uses, by basin	Historical review of the economic and land use literature to assess its importance (production, used areas)
	Assessment of the water quality	Historical review of water quality background data for each basin, by river segment, especially for major ions and physical parameters (minimum, maximum, mean, variance)
	Determination of minimum effect concentrations for various contaminants in various media for various water uses	Comparison of data from laboratory bioassays, field studies, and literature on ecotoxicology
f) Compliance with water quality guidelines and objectives	Location, importance, and frequency of noncompliance measurements	Crosstables comparing the number of noncompliance measurements to the total number of samples; graphs (histogram of concentrations, plot of levels vs. time); determination of hot spots and hot periods; calculation of percentiles, medians, means, minimums, and maximums of data, and mean and variance of excess levels
g) Assessment of the effectiveness of implemented legislation or of the impact of the implementation of a project (e.g., dam)	Determine if water quality has improved since the implementation of regulations or project and measure the importance of change	Comparison between two temporal series of data using ANOVA and Student t-Test on the means; plots of levels of contaminants vs. time; intervention analysis
h) Fate of contaminants in the aquatic ecosystem	Determine in which media and as which form a given contaminant tends to accumulate	Comparison of mean concentrations and standard deviation of a given contaminant between various forms and various media from samples collected at a given site and a given time
i) Prediction of the behaviour of a contaminant; pathway models	Identification and quantification of interactions between a given pollutant and other indicators of the quality of the aquatic environment	Look at covariance or correlation between parameters; quantification of interrelationships by using simple (e.g., regression) or complex empirical models; factorial analysis to identify groups of parameters showing the same behaviour or explaining the measured variability
j) Optimization of an implemented network	Reduce number of stations, number of measured parameters, or sampling frequencies	Calculation of confidence intervals for each parameter; analysis of autocorrelation for various sampling frequencies; ANOVA by season for each parameter; cluster analysis correlation

3.10 Reporting

Step 10, reporting, provides the bridge between scientific data collected and information usable by environmental managers for decision making, or by the public for assessing if water uses are impaired. Thus, there is often a need for various reports from a given water quality monitoring activity, depending on the client. Moreover, it must be emphasized that most clients are seeking information rather than data. Questions often asked are: Is the water quality getting better or worse? Are contaminant concentrations increasing or decreasing? Is there a risk for health? Can water be used for such and such purpose?

3.11 Management Decisions

Step 11 is the final review of information produced from the aquatic environmental quality assessment to determine if the original goals are met. Once contaminant concentrations, distribution, or effects are known, associated environmental health risks can be assessed and forecasts can be made. Managers can make decisions about the development of new environmental policies, the implementation or strengthening of regulations or objectives, or the need for specific in-depth studies. One should use monitoring data as a feedback mechanism to make predictions following various decision options.

If some monitoring goals are not met, or are not met efficiently, the monitoring program must be optimized, i.e., redesigned so that appropriate and sufficient data will be collected in the most cost-effective manner.

CONCLUSION

The assessment of contaminant-related issues in the aquatic environment is an important part of the mandate of WQB. A review of WQB activities shows a historical trend toward those types of assessment, but important constraints limit their implementation. A strategy to assess exposure and effects of contaminants in the aquatic environment would be of great advantage for water managers in that it would assist in coordinating and optimizing work done and identifying what more needs to be done and how.

The use of a conceptual model of the aquatic environment, the determination of water quality issues to be studied, the definition of monitoring goals and rationales, the review of historical information, the choice of an operational approach, sampling design, network implementation and operation, data management and reporting, and management decision making, as suggested here, are all components necessary to any strategy. These components are linked by the flow of water quality information initiated by the monitoring goals. But the process does not end with management decision making. Any water quality assessment is a stepwise approach, i.e., generated information is used partly to optimize the assessment procedure itself and to focus on emerging issues once these are identified.

It is not the purpose of this paper to assess what new resources are needed to implement the strategy. It is felt, rather, that the strategy will allow a better use of actual resources. The implementation of the strategy will facilitate coordination of the activities of all participants at the local, regional, or national level with laboratory services (i.e., quality assurance, analysis of organics), as well as with the research communities (i.e., research on bioaccumulation, degradation rates, etc.).

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